



An experiment-driven energy consumption model for virtual machine management systems

Mar Callau-Zori, Lavinia Samoila, Anne-Cécile Orgerie, Guillaume Pierre

► To cite this version:

Mar Callau-Zori, Lavinia Samoila, Anne-Cécile Orgerie, Guillaume Pierre. An experiment-driven energy consumption model for virtual machine management systems. [Research Report] RR-8844, IRISA; Université de Rennes 1; CNRS. 2016. hal-01258766

HAL Id: hal-01258766

<https://inria.hal.science/hal-01258766>

Submitted on 19 Jan 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



An experiment-driven energy consumption model for virtual machine management systems

Mar Callau-Zori
Lavinia Samoila
Anne-Cécile Orgerie
Guillaume Pierre

**RESEARCH
REPORT**

N° 8844

January 2016

Project-Team Myriads



An experiment-driven energy consumption model for virtual machine management systems

Mar Callau-Zori*
Lavinia Samoila*
Anne-Cécile Orgerie†
Guillaume Pierre*

Project-Team Myriads

Research Report n° 8844 — January 2016 — 26 pages

Abstract:

As energy consumption is becoming critical in Cloud data centers, Cloud providers are adopting energy-efficient virtual machines management system. These systems essentially rely on “what-if” analysis to determine what the consequence of their actions would be – and to choose the best one according to a number of metrics. However, modeling energy consumption of simple operations such as starting a new VM or live-migrating it is complicated by the fact that multiple factors takes part. It is therefore important to identify which factors influence energy consumption before proposing any new model. We claim in this paper that one critical parameter is the host configuration, characterized by the number of VMs it is currently executing. Based on this observation, we present an energy model that provides energy estimation associated to VM management operation, such as VMs placement, VM start up and VM migration. The average relative estimation error is lower than 10% using the transactional web benchmark TPC-W, making it a good candidate for driving the actions of future energy-aware cloud management systems.

Key-words: Green computing, Cloud computing, virtual machine management.

Acknowledgments: This work was partially supported by the EcoPaaS project of the Brittany Region (project number 8269).

* IRISA/Université de Rennes 1, mar.callau-zori@irisa.fr, lavinia.samoila@irisa.fr, guillaume.pierre@irisa.fr.

† IRISA/CNRS, anne-cecile.orgerie@irisa.fr.

An experiment-driven energy consumption model for virtual machine management systems

Résumé : La consommation d'énergie devient critique dans les centres de données en nuage. Les fournisseurs cloud adoptent donc des systèmes de gestion des machines virtuelles avec des critères pour l'efficacité sur la consommation énergétique. Ces systèmes reposent essentiellement sur des analyses de type "what-if" pour déterminer les conséquences des actions – et pour choisir la meilleure action selon plusieurs métriques. Cependant, la modélisation de la consommation d'énergie d'opérations simples, tel que le démarrage d'une nouvelle machine virtuelle ou la migration en direct, est une tâche complexe parce que de multiples facteurs participent aux modèles. Nous proposons un modèle simple pour l'estimation des consommations énergétiques liées aux différentes opérations de gestion des machines virtuelles.

Mots-clés : Informatique en nuage, gestion de machines virtuelles, économies d'énergie.

Table of contents

1	Introduction	4
2	Related work	6
2.1	VM power models	6
2.2	Live-migration power models	7
3	Experimental facts	8
3.1	Impact of the number of VMs allocated in a host	9
3.2	Impact of VM start up	10
3.3	Impact of VM migration	11
3.4	Impact of workload profile	14
3.5	Impact of GPU accelerator	15
4	Modeling energy	16
5	Experimental results about model validation	17
5.1	First use-case: VM allocation	17
5.2	Second use-case: starts and migrations together	18
6	Learning model parameters in a real system	19
7	Discussion	21
8	Conclusions	22

1 Introduction

Context Advances in distributed systems have historically been related to improving their performance, scalability and quality of service. However, the energy consumption of these systems is becoming more and more concerning. Although the emergence of Cloud Computing has led to a massive virtualization of the resources, their energy cost is still real and rapidly increasing due to a growing demand for Cloud services. As an example, for 2010, Google used 900,000 servers which consumed 1.9 billion kWh of electricity [20]. This ever-increasing electricity bill puts a strain on operating expenses, and has thus led researchers to look for more energy-efficient frameworks.

The most common approach to save energy in Cloud infrastructures consists in consolidating the load on the smallest possible number of physical resources [29], thus making it possible to switch idle machines to sleep modes [36]. To this end, scheduling heuristics are used for allocating new virtual machines (VMs) or for re-allocating running VMs in conjunction with live-migration techniques for dynamic consolidation, with a close-to-zero downtime.

In this paper, we propose and evaluate an experiment-driven model to estimate the energy consumption associated to VM management operations, such as VM placement, VM start up and VM migration. This model provides reliable and accurate energy consumption values, which are required by energy-aware VM management frameworks in order to take efficient decisions.

Motivating example Cloud providers offers on-demand computational resources in the form of virtual machines, disks and network functions. These resources can be used freely by the tenants. Meanwhile, the provider may perform VM management operations, such as create/delete, suspend/resume, shut down/restart and migrate to reduce the energy consumption of the platform or simply for maintenance purposes or to redistribute the load. These operations can be performed in different ways leading to different energy consumption.

A scenario based on consolidation illustrates the variability in energy consumption of two typical algorithms in Figure 1. The consolidation goal is to reduce the number of physical hosts where VMs are allocated. The example starts with four identical hosts (same hardware) and eleven identical VMs uniformly distributed among the hosts (left-side of Figure 1). The final configuration in both cases has only two provisioned hosts – allowing to switch off the two others.

Figure 1 on the bottom shows the consumption for the two algorithms: the *first-fit consolidation* where all VMs are moved to host 1, and the *balancing consolidation* where VMs are uniformly distributed between host 1 and host 2. Our experimental results provide the energy overhead due to the migrations and the power consumption of the hosts after the re-configuration. Despite the numerous approaches based on the first-fit algorithm in the literature [29], the balancing consolidation performs better on this example. Indeed, it saves 12% of the energy with respects to the first-fit consolidation for the migration operations, and the final consumption of the two hosts is less by 4.5% with this configuration. In particular, this example clearly highlights that identical VMs are not equal in terms of energy consumption.

This paper argues that VM management systems must be aware of the energy consumption of the different operations (such as VM allocation, VM start up and VM migration) and must have an accurate energy model of their physical hosts depending on their configuration (i.e. number of hosted VMs) in order to be truly energy-efficient. More details about these experiments are provided in Section 6.

Energy-efficient VM management techniques On the one hand, heuristic-based methods for VM allocation take practical decisions to satisfy immediate goals, such as maximizing the number of idle hosts [4, 5, 8], minimizing the number of VM migrations [23], or determining

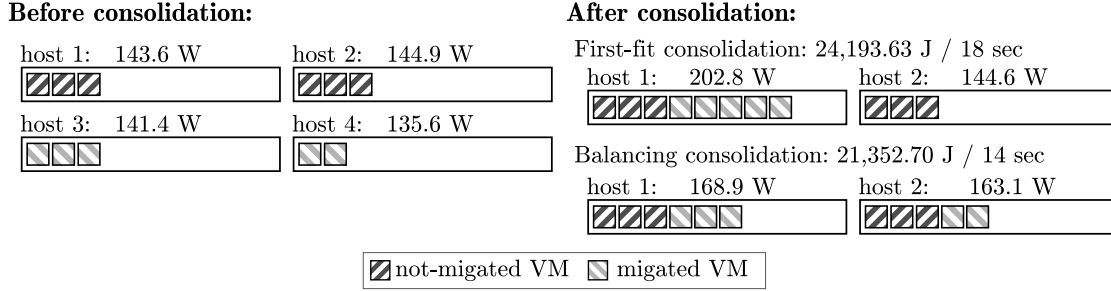


Figure 1: Energy overhead depends on the consolidation algorithm.

the most energy-efficient available host for each new VM [2, 31]. However, solutions derived from heuristics are not guaranteed to be optimal in the long term, especially in heterogeneous environments [30]. Therefore, it is unclear which heuristic will guarantee the most energy-efficient system. On the other hand, although live-migration leads to almost no performance degradation, it is not energy-free. While for the hosts, the migration cost mainly depend on the VM size and network bandwidth [42, 45], the sequential aspect of multiple VMs migration has also an impact [47], and widely-used Cloud software platforms, like OpenStack [35] for instance, perform multiple migrations in a sequential way. These points enlighten the necessity of accurate energy models of VM management operations for applying the adequate energy-efficient technique.

However, defining an accurate energy consumption model for VMs is still an open challenge [30]. This is mainly because the energy consumption depends on multiple factors: the workload, the hardware, the host configuration, the VM characteristics, etc. Furthermore, determining the suitable parameters which describe the inherent properties is crucial to enforce the model. Previous work [7, 6, 12, 14, 19, 21] has already proposed models based on factors, such as the server hardware, the IaaS-software (such as the hypervisor and the management software) or the VMs resources (such as CPU, memory, disc and cache). However, the impact of the host configuration has been slightly studied. Related energy models are further detailed in Section 2.

Energy model for VM management operations The paper presents directions for a comprehensive energy-estimation tool assuming that the VM management system performs actions sequentially, as it is often the case in current Cloud software platforms [35]. This means that if the system receives two requests (e.g. a VM creation and a VM migration), it waits for the first one to finish before executing the other one. The model is built over a wide set of experiments aiming at observing variations according to VMs management operations, host configuration and workload application. This experimental study (Section 3) provides helpful information claiming for an energy model based on VMs management operations and hosts configuration. The proposed model (Section 4) takes into account the host configuration, and in particular the number of already running VMs on this host.

In [10], the authors study the energy consumption according to the number of VMs allocated in a single host and to the number of virtual CPU. Similarly to our motivating example, they show that the energy consumption depends on the previous configuration of the host. However, in their experiments, the number of virtual cores is never greater than the number of physical cores. So, they do not explore overcommit situations, which are frequent in Cloud platforms [3, 9], although not studied in literature from an energy point of view. In this paper, we explore host configurations with CPU overcommit, and we show that the proposed model works for these overcommit situations.

Evaluation This paper targets online applications hosted by web servers on Cloud infrastructures and represented here by the TPC-W benchmark [44] for evaluation purposes (Section 5). TPC-W is a transactional web benchmark simulating a Web-based shop for searching, browsing and ordering books. We have validated the proposed energy model through two use-case scenarios using OpenStack as the Infrastructure-as-a-Service Cloud layer. In the first scenario, the system has a workload peak which produces an increasing number of VMs allocated on the physical host. In the second scenario, migrations and VMs starts-up occur in a system with several hosts. In both cases, the model is able to predict the involved energy consumption with an average relative error lower than 10%, and thus to adapt the system accordingly.

The applicability of the model is studied over a realistic scenario (Section 6). The model is trained over a simple scenario and then applied to a more complex scenario on which it is used to evaluate the energy-efficiency of three consolidation algorithms. We hereby demonstrate the ability of the model to provide valuable results for a what-if analysis. Experiments on a real platform exhibit an average relative error lower than 10%. The advantages and drawbacks of our model are further discussed in Section 7.

Contributions In summary, in this paper: (1) we provide an experimental study of the energy consumption of VM management operations under realistic workload conditions including overcommit situations, (2) we propose an energy model for physical host consumption, (3) we evaluate the accuracy of this model via experimentation on a real system deploying web applications, and (4) we show its applicability and how it can significantly help Cloud management systems to take truly energy-efficient decisions.

2 Related work

Energy models have mainly been studied in the context of a single host, a single virtual machine or an entire cluster [33]. The virtualization proposes to improve resource utilization through dividing one physical server into multiple isolated virtual machines. Resources sharing makes complex to leverage experiences from previous efforts on energy estimation in single host [18, 26, 32, 37, 38, 39] and on energy estimation in cluster models for data centers [15, 24].

In virtualized environments, we distinguish previous models to estimate power consumption of a single VM and previous models to estimate power overhead during live-migration. In the rest of this section, we discuss research in both directions.

2.1 VM power models

In [19], the authors propose a linear power model in terms of CPU utilization, memory (last level cache misses) and disk, with a linear regression to learn model parameters. Authors achieve a total power error on the host of 1.6 Watts to 4.8 Watts.

Another linear model is presented in [7] considering CPU, memory, disk and cache. The principal component analysis obtains a high correlation between CPU and cache; and between disk and DRAM. This fact motivates the utilization of two regression models to estimate model parameters. The results show that the model is able to predict energy power with an average mean error of 7%.

In [21], the authors present a linear model considering CPU and memory. They indicate the importance in energy consumption of the utilization of the cache levels and memory level parallelism. The evaluation shows that VM power is estimated within 7% of the measured value.

Gaussian mixture models are proposed in [14] to estimate power consumption based on architecture metrics (such as IPC, cache, memory usage, among other performance monitored

counters). In the training phase, a set of Gaussian mixture models that represent different architecture interactions and power levels are obtained. An average prediction error of less than 10% is achieved.

Another linear model based on CPU utilization, memory and disk is proposed in [6]. This model is learned according to the dynamic voltage frequency (using the DVFS technique). For the evaluation, up to 10 virtual CPUs are allocated in servers with 2 cores. The results exhibit an average error lower than 5%.

Based on the major power consumer which is the CPU for a server, a process-level power estimation is presented in [12]. A polynomial regression is applied to estimate the power consumed by the CPU in terms of the frequency and the `unhalted-cycles` for each active process and core. The average estimation error achieved is below 10%.

In the previous work, we observe three main characteristics. Firstly, presented models assumes that a VM always consumes the same amount of energy if the VM performs similar work (e.g. similar utilization of CPU, memory and cache). Thus, these contributions assume that energy consumption of a VM is independent of the number of hosted VMs in the hosts. Secondly, the total number of virtual cores used the running VMs is at most the number of physical cores (except in [6]). However, in real Cloud platforms, over-provisioning is common for users, leading Cloud providers to resort to over-commitment [3, 9]. Hosting more virtual cores than the number of physical ones can consequently affect the assumption that energy consumption of a VM is independent of the number of hosted VMs on the server. Thirdly, most of the previous work is evaluated through benchmarks specifically designed to stress CPU, memory and/or I/O. However, in real environments, resources do not reach such high utilization levels, mainly to guarantee performance and quality of service. Only work presented in [12] employs for their evaluation SPEC JBB 2013 [13], a benchmark which emulates a supermarket company.

2.2 Live-migration power models

Previous analyzes about energy overhead during live-migration show differences in the energy consumption for source and destination hosts [16, 37, 40].

In [25], a model based on the VM memory size, the memory transmission rate and the memory dirtying rate is proposed. The authors not only estimate the energy overhead during migration, but also the network traffic overhead and the downtime. However, they assume that energy consumption is similar in source and destination hosts. The evaluation using Xen hypervisor [46] shows an average error below 10%.

It is shown in [42] that energy overhead during migration depends on RAM and available bandwidth. Based on this work, the authors propose in [41] a power model for estimating the energy overhead of live-migration for an idle VM. The average error using KVM hypervisor [22] is lower than 10%.

In [27], the authors present a model depending on the CPU utilization (considering both hosts and the migrated VM), the VM memory utilization, the available bandwidth and the memory dirtying rate. The evaluation is conducted through live-migrating a VM in a host where there are already 8 running VMs. Results using Xen hypervisor with a CPU and memory intensive workload shows a normalized root mean square error lower than 18%. Authors expended this work in [28] by proposing a model for network transfers achieving a normalized root mean square error lower than 9%.

One can notice that, in the previous work, only one VM is migrated for the validation of the various models. However, the consolidation usually imply to deallocate all the VMs of a host. Therefore, migrations are produced consecutively and energy overhead can be affected due to these successive migrations.

Table 1: TPC-W configuration parameters.

Number of browsers	<i>100</i>
Transaction Mix	<i>Factory</i>
Ramp-up time	<i>600 sec</i>
Ramp-down time	<i>600 sec</i>
Measurement time	<i>1800 sec</i>
Slow-down factor	<i>1.0 (default)</i>
Nb. customers	<i>144000</i>
Nb. items	<i>10000</i>
Think time multiplication	<i>0.25</i>
Maximum errors allowed	<i>unbounded</i>
Maximum number of images downloaded at once	<i>4</i>

3 Experimental facts

We conducted an in-depth experimental analysis of VM management operations in order to understand their impact on energy consumption. The experiments have been executed on Grid’5000 [1], a French test-bed designed for experiment-driven research. We base experiments on four servers equipped with two 6-cores Xeon E5-2630@2.3GHz processors (12 cores in total), 32 GB of RAM, 10 Gbps Ethernet and embedding with a Nvidia Tesla M2075 GPU accelerator. The power consumption is collected externally at each second for each server using adapted watt-meters provided by the SME Omegawatt. We use OpenStack Icehouse [35] to dynamically create VMs through the KVM hypervisor [22]. VM deployment is relying on an NFS server (Network File System) for the storage. This solution is well suited for web servers, and has a facilitating impact on VM live-migration. The VMs are configured with 4096 MB memory, 80 GB of virtual disk and 4 virtual CPUs. This configuration is similar to Amazon EC2’s ‘m4.xlarge’ instance type, although with less memory [17]. As the hosts considered in this experimental study comprise 12 cores each, without overcommit, they can only run 3 of such VMs each.

We create realistic workload by running the MySQL+Java version of TPC-W in the VMs. TPC-W is a transactional web benchmark which simulates the activities of a business oriented transactional web server [44]. TPC-W allows three profiles of web traffic (called *ordering*, *browsing* and *shopping*). The main traffic profile used is *ordering*, where the number of book’s purchases is large – this means, large number of write operations into disk. Other TPC-W parameters are summarized in Table 1. TPC-W measures the throughput in number of WIPS (Web Interactions Per Second) that the server manages to sustain.

Summarizing, each VM has the virtual hardware described above and runs a TPC-W server. We therefore measure two metrics: the power consumption of each physical server, and the throughput measured in WIPS of each TPC-W server, each one running in a single VM. Experiments ran once on the four different servers.

We study three kinds of VM management operations: the VM allocation in a single host (Section 3.1), the VM start up (Section 3.2) and the VM migration (Section 3.3) Then, we study the impact of the workload profile in Section 3.4 and the influence of the GPU accelerator in Section 3.5.

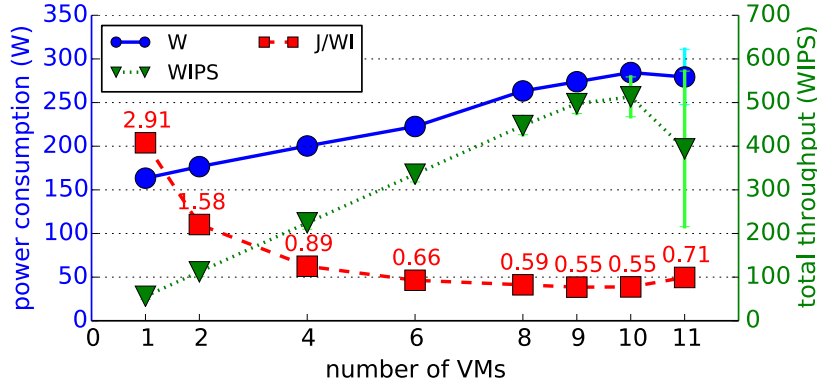


Figure 2: Power consumption and throughput when varying the number of VMs in the host.

3.1 Impact of the number of VMs allocated in a host

Our first experiment evaluates how many VMs a single host can manage in an energy-efficient way. The scenario consists in increasing the number of VMs put on a single host. Figure 2 shows the power consumption and throughput depending on the number of VMs running on the host. The X-axis shows the number of VMs in the host, whereas the Y-axes present three metrics: the power consumption in Watts (blue circles, left side), the total throughput over all VMs in WIPS (green triangles, right side), and the power/performance ratio in Joules/WI (Joules over number of web interactions, red squares).

We see that the power consumption and VM throughput increase up to 11 VMs per host, but increasing is linear up to 8 VM. If we keep increasing the number of VMs, then the consumed power starts decreasing from 11 VMs and throughput also drops at 11 VMs. The optimal power/throughput ratio is obtained using 9-10 VMs per host.

If focusing only on throughput, the most efficient configuration is the one ensuring linear scalability: so 8 VMs per host at maximum. However, maintaining a maximum of 8 VMs per host is not the most power-efficient case. For example, a system with 1 host with 10 VMs spends less power (219.84 W) than a system with 2 hosts: one with 8 VMs and another with 2 VMs, (335.76 W) saving 52.73% of power. This relationship between power and throughput corresponds to the red line on Figure 2, and shows that placing either 9 or 10 VMs per host is more power-efficient than staying with 8.

Regarding power consumption in details, Figure 3 presents a synthetic view of the power consumption distribution using box-plot. Classically, the box-plot has a box and a whisker plot for each case. The box extends from the 25th to 75th percentile with a red line at the median. The whiskers extend from the box, and points outside the whiskers are considered outliers. Distances from whiskers to box are a factor of 1.5 of the interquartile range (box height). Finally, outliers are plotted individually.

In the power distribution, Pearson correlation coefficient (0.97) with the number of VMs in [1, 10] shows a strong linear correlation between the number of VMs and the power consumption. A special case occurs for 6 VMs: where the 75th percentile (top on the box) is lower than the regression line.

As we said, previous work assumes that the power consumption is a linear function in the number of VMs. Concretely, the assumption on the power of the host is $P_{\text{host}} = P_{\text{idle}} + \sum_{v \in \text{VMs}} P_v$, where P_{idle} is the idle power of the host and P_v is the power of the VM v . In

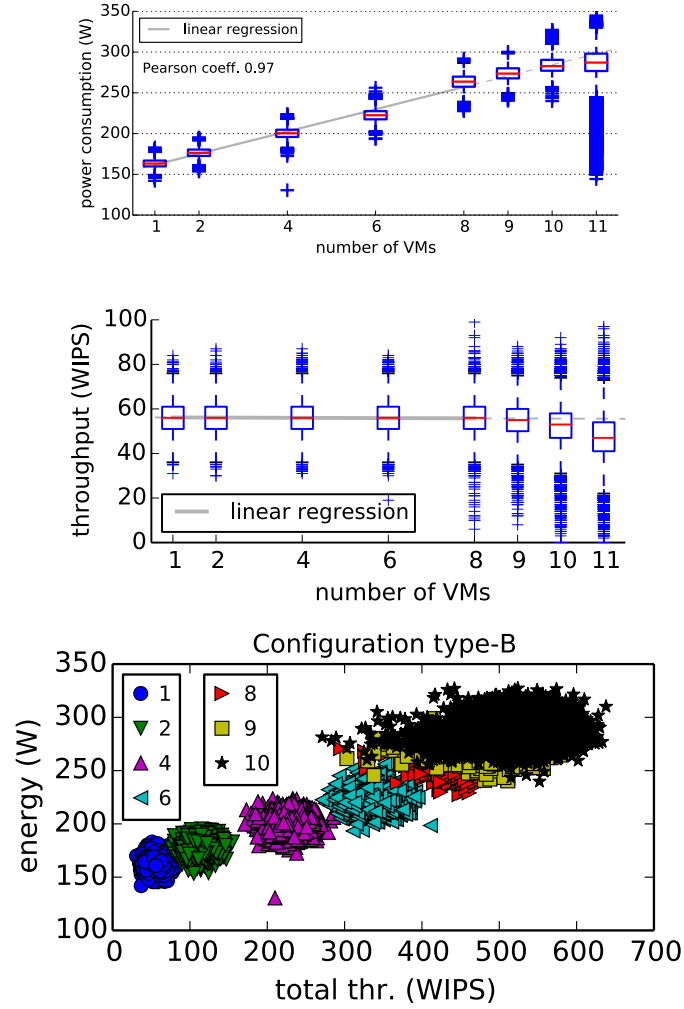


Figure 3: Details on power consumption by increasing the number of VMs in the host.

our case, the idle power is 95.92W (measured independently) and all the VMs perform the same work having the same consumption before saturation (less than 9 VMs). However, in Table 2, we show the average power value for one VM, P_v , and hereby evidencing that the power consumed in one VM depends on the number of running VMs on the host.

From this first experiment, we can draw several conclusions. Firstly, in order to achieve energy-efficiency, allowing small degradation of the throughput can generate important power savings, as it has already been noticed in [30]. Secondly, power consumption is significantly impacted by the host configuration (i.e. the number of running VMs).

3.2 Impact of VM start up

We now investigate the power consumption overhead and throughput degradation during a VM creation. Figure 4 shows an example of VM creation on a host already running one VM. After 1200 seconds, a new VM is created. VM start-up finishes when TPC-W starts to run (in this

Table 2: Average power consumption per VM.

Nb. of VMs	1	2	4	6	8	9	10
Power per VM (W)	67.5	40.3	26.1	21.1	20.9	19.8	18.9

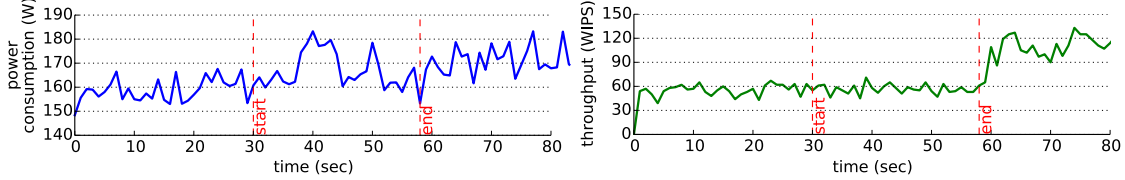


Figure 4: Example of VM start-up: power consumption and host throughput.

example it takes 28 seconds). As expected, the throughput does not increase during the creation. However, starting a new VM causes a spike in power consumption (with consumption peak greater than 180W).

After this example, we provide a general study in Figure 5 representing average power consumption and throughput variation during a VM creation. The left side (blue colors) corresponds to the total power consumption, while the right side (green colors) represents the average throughput (WIPS) across all the VMs. Power consumption bars (resp. throughput bars) are split in two: first, the power consumption (resp. throughput) before VM start up; and second, the power consumption (resp. throughput) observed during VM start-up (averaged over the start-up duration).

While the power consumption is always greater during start-up, the throughput does not suffer degradation except for 9 VMs. One can notice that degradation happens passing from 9 to 10 VMs, which confirms the previous conclusion asserting that the 10 VMs case breaks the linear scalability.

Details about power consumption during start-up process are presented in Figure 6. The gray line represents the linear regression over data obtained from 1 to 8 VMs before the VM start-up. We see that power increases during start-up from 1 to 8 VMs. Moreover, power consumption overhead is smaller for 6 VMs than for the other cases.

We have explored this phenomenon more deeply in Table 3 representing the power overhead percentage of VM start-up. We observe a decreasing trend in the power overhead of 1-5 and 7-9.

We clearly see that starting up a VM is not power-neutral. Hence an energy-efficient system should guarantee a minimum lifetime after VM creation. Furthermore, this minimal lifetime depends on the previous configuration on the host.

3.3 Impact of VM migration

We now evaluate the impact on power consumption and throughput of VM live-migration. The scenario consists of migrating a VM between two hosts which already contain some running

Table 3: Average power consumption overheads upon VM start-up.

Nb. of VMs	1	3	5	7	8	9
Power overhead	5.1%	3.2%	3.1%	6.0%	3.3%	1.9%

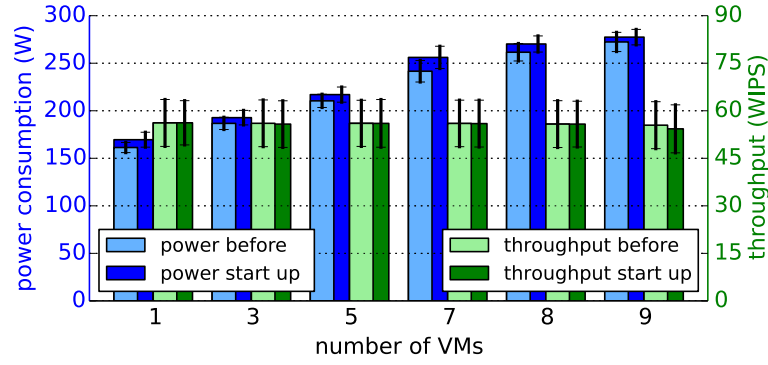


Figure 5: Throughput and power consumption overheads upon VM start-up.

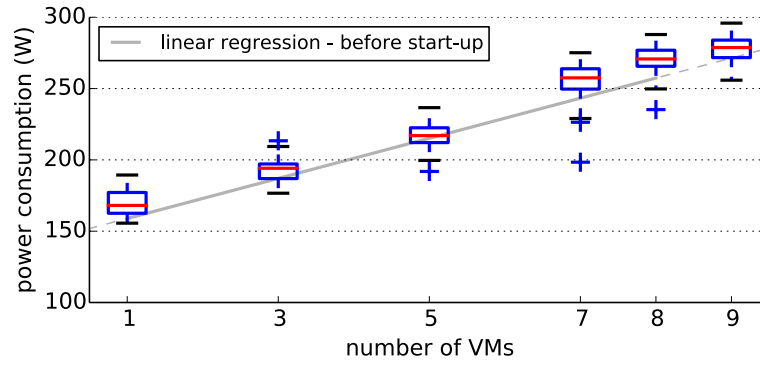


Figure 6: Details in power consumption overhead upon VM start-up.

VMs. Under the live-migration with pre-copy approach [11], the VM continuously runs while its memory is copied from source host to destination host in several runs (pre-copy phase). Requests are processed by the VM in the source host, until the system is notified of the pre-copy phase termination. At this point, the VM is suspended to perform the last copy (stop-and-copy phase). Finally, requests start to be processed by the VM in the new location.

Figure 7 presents the experimental results of a VM migration in terms of power (top) and throughput (bottom). Throughput is equal to zero during few seconds, waiting for the system to be informed of the new location. Power consumption overhead is investigated in the source and in the destination hosts separately.

During migration, the power consumption of source host starts to decrease, while in the destination host, it increases. Dotted lines represent the average power consumption in source and destination hosts, before and after migration. Interestingly, it takes about 20 seconds after the end of the migration for both hosts to reach power consumption at levels corresponding to the number of allocated VMs. Hence, the experiment show that live-migration produces power consumption overhead beyond the migration time.

For a deeper understanding of the impact of migration, we present a general study where a VM is migrated after 1200 seconds. Source and destination hosts already have a number of static (i.e. non-migrated) VMs. This means that we distinguish three types of VMs: migrated VM (*mig*), static VMs in the source host (*src*) and static VMs in the destination host (*dst*).

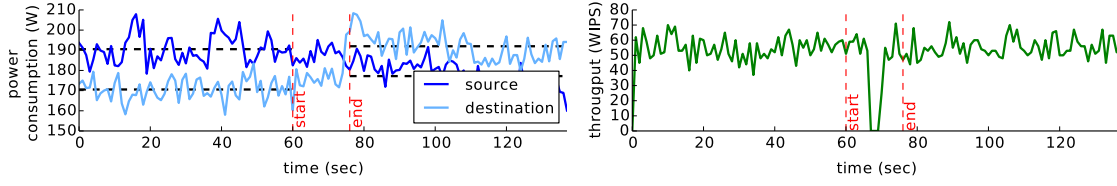


Figure 7: Example of power consumption and throughput upon VM migration.

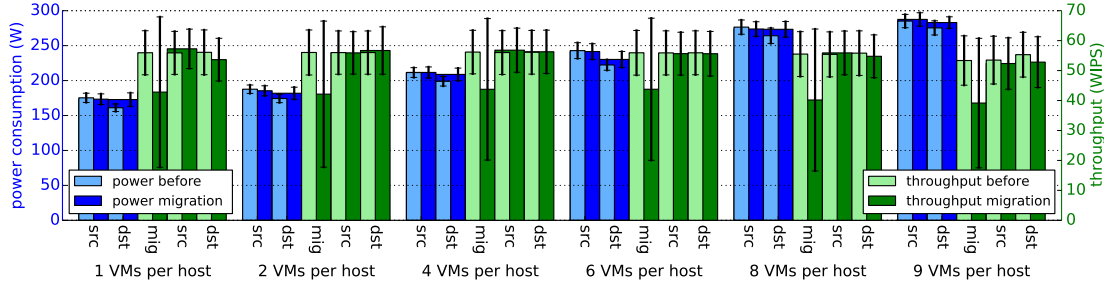


Figure 8: Overheads upon VM migration.

In the following, for the sake of clarity, we take the same number of static VMs in source and destination host for a given experiment ($st_src = st_dst$).

Results are summarized in Figure 8. The X-axis represents the number of static VMs for each host (source and destination). Fixing the number of static VMs, we have the power consumption of the source and destination host: in lighter blue the power consumed before migration and in darker blue the power consumed during migration. On the throughput side, we consider three metrics: one for the migrated VM, one for the static VMs in the source host, and, respectively, in the destination host.

During migration, the power consumption of the destination host increases (1.35% – 7.63%), and in the source host, it does not have a stable behavior either (–2.96% – +0.92%).

Details about the total power consumption overhead are provided in Figure 9. The total power is the accumulated power consumed in the source and destination hosts during migration. The gray line represents the regression line over the total power consumption before the migration. The power increment is more significant in extreme cases (VMs per host = 1, 2, 8 and 9), while for 4 to 6 VMs per host, power does not significantly increase during migration. As expected, the total power consumption increases during migration (0.55% – 2.69%).

As explained in the example from Figure 7, it takes time for the power consumption in the destination host after migration to stabilize. To explore this issue, we determine the minimum time after a migration where the average power consumption in the destination host, on a window of 10 seconds, is less or equal than the percentile 60% of the power consumption in source host before the migration. We are exploiting the fact that after migration, the destination host allocates the same number of VMs than the source host before the migration. These times are summarized in Table 4. We observe a non-negligible impact on the power consumption: the time to recover expected power consumption varies between 1 and 271 seconds depending on the host configuration.

The throughput of non-migrated VMs is not affected by the migration, as shown in Figure 8. However, the migrated VM has an important degradation reducing its throughput by 21% to 29%. Although migration takes only a few seconds, the impact of the resulting throughput degradation

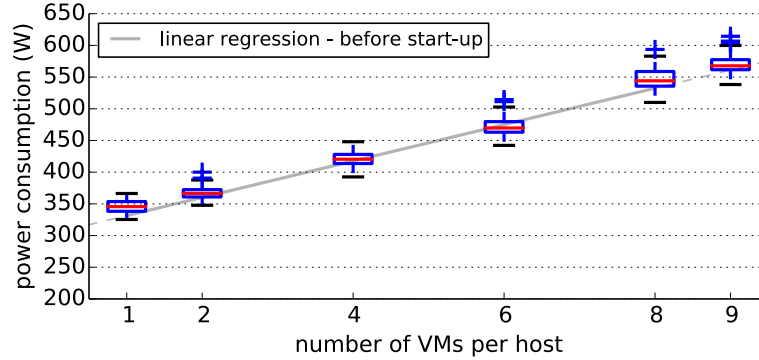


Figure 9: Details in power consumption overhead upon VM migration.

Table 4: Time to recover expected power consumption after a VM migration.

Nb. of VMs	1	2	4	6	8	9
Delay (sec)	1.3	14.8	36.5	97.0	61.8	271.5

will largely depend on the moment it happens. The average down-time varies from 2.73 to 3.30 seconds being similar to that obtained in the literature [43]. We expected the downtime to be independent on the hosts configuration because hosts are not saturated. However, our experimental study shows that it is not the case.

As other studies [37] have already pointed, live-migration produces energy overhead occurring mainly in the destination host. Moreover, we have also observed that migration produces power consumption overhead also after the migration time. This fact is a sensitive issue in consolidation, because migrations are often produced consecutively. Finally, we see that the power consumption overhead depends on the number of running VMs in the hosts.

3.4 Impact of workload profile

We now evaluate the impact of the client behavior, thus influencing the workload on the servers. As previously stated, TPC-W allows to simulate three different profiles by varying the ratio of browse to buy transactions: shopping, browsing and ordering.

Figure 10 shows a scenario where the number of VMs put on the same host increases for the TPC-W profiles *ordering* and *browsing*. While the X-axis represents the number of VMs in the same host, the Y-axes represent two metrics: the average power consumption in Watts (blue colors, left side) and the average throughput in WIPS (green colors, right side).

We observe that throughput is equal for the two profiles between 1 and 9 VMs. From 10 VMs however, *ordering* workload starts to degrade, reaching saturation at 11 VMs. On the other hand, placing less than 13 VMs with *browsing* workload has no negative impact on the throughput. This behavior – faster host saturation with *ordering* workload than with *browsing* workload – was expected, because for *ordering*, more writes to the disk are performed.

In terms of power consumption, it is larger under *ordering* than under *browsing*, while both have the same throughput. The difference is greater as the number of VMs is increasing. Moreover, under *ordering* the power consumption slope changes at 6 VMs, while under *browsing* the slope break happens at 8 VMs.

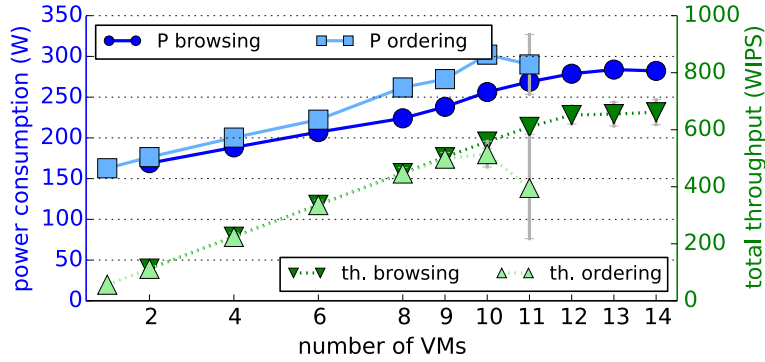


Figure 10: Power consumption and throughput according to workload profiles.

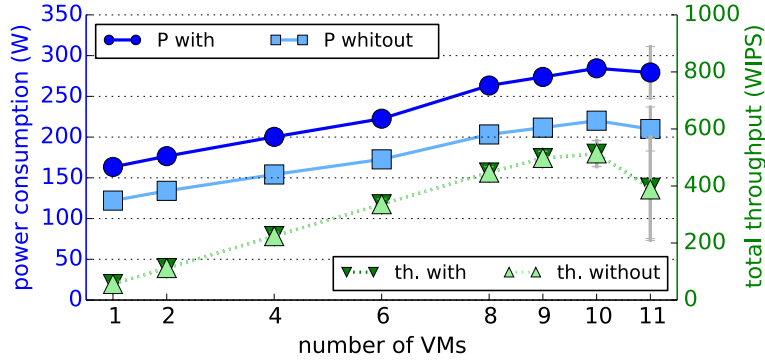


Figure 11: Power consumption and throughput according to GPU accelerator.

3.5 Impact of GPU accelerator

In the previous experiment, all the servers are equipped with an Nvidia Tesla M2075 GPU accelerator. GPU accelerator is designed to use a graphics processing unit (GPU) with a CPU in order to accelerate scientific, analytics, engineering, consumer, and enterprise applications [34].

We investigate the impact of having a GPU accelerator embedded on servers – although we are not using it. Figure 10 presents the results increasing the number of VM in the host for servers with the GPU accelerator and servers without it (same hardware configuration). As in the previous figures, the X-axis represents the number of VMs in the same host, the Y-axes represent two metrics: the average power consumption in Watts (blue, left side) and the average throughput in WIPS (green, right side).

As expected, having a useless GPU accelerator does not improve performance. However, even if the GPU accelerator is not used, the power consumption of servers with GPU accelerator is 22% larger than without it. Power is wasted if unsuitable servers are used to allocate VMs that do not exploit all the hardware capabilities.

Table 5: Model parameters in a host h running m VMs.

VM operation	Model parameter	
	Variable	Description
-	$P(m)$	Power consumption of a host with m VMs (W)
start up	$E_{\text{start}}(m)$	Energy consumption (J)
	$T_{\text{start}}(m)$	Time duration (sec)
migration	$E_{\text{src}}(m)$	Energy consumption in source (J)
	$E_{\text{dst}}(m)$	Energy consumption in destination (J)
	$T_{\text{mig}}(m)$	Time duration (sec)

4 Modeling energy

Next to the experimental facts studied in the previous section, we formalize an energy model for the VMs management operations. The model is additive, this means the energy consumption of each VM operation (start up and migration) is added to achieve the total energy consumption in a time period.

At every time t , the system can start a VM management operation. The energy consumption of the hosts depends on this choice. Lets $E(t, h)$ the *reconfiguration energy cost* in the host h , that is the energy overhead during the whole VM operation concerning host h ; and t the *reconfiguration time* meaning the time to apply the changes. Noting that while start up and migration imply energy overhead in a interval time; if the systems keeps the same VM placement, the energy consumption corresponds just to one second (assuming we need to provide energy consumption each second).

From results of Section 3, we know that the reconfiguration energy cost depends on the previous state of the host. Therefore, in Table 5, we define the model parameters according to the number of running VMs and the VM operation associated.

Given m the number of VMs in a host h previous to the reconfiguration, the reconfiguration energy cost takes the following values:

$$\left\{ \begin{array}{l} \text{Neither VM start up nor migration begins at time } t \text{ in } h: \\ \quad E(t, h) = 0 \\ \text{A VM start up begins at time } t \text{ in host } h: \\ \quad E(t, h) = E_{\text{start}}(m) \\ \text{A VM migration begins at time } t \text{ implying host } h: \\ \quad E(t, h) = E_{\text{src}}(m) \quad \text{if } h \text{ is the source host and has} \\ \quad \quad \quad m + 1 \text{ VMs at } t \\ \quad E(t, h) = E_{\text{dst}}(m) \quad \text{if } h \text{ is the destination host and} \\ \quad \quad \quad \text{has } m \text{ VMs at } t \end{array} \right.$$

An illustrative example is provided on Figure 12 for the VM start up case. The model has to learn the different parameters, namely $P(m)$, $P(m + 1)$, $E_{\text{start}}(m)$ and $T_{\text{start}}(m)$.

Finally, the energy consumption of a host during a time period I (during which the number of VM does not change) is the sum of reconfiguration energy costs during this period plus its regular energy consumed by its m VMs:

$$\sum_{t \in I} E(t, h) + P(m) \times I$$

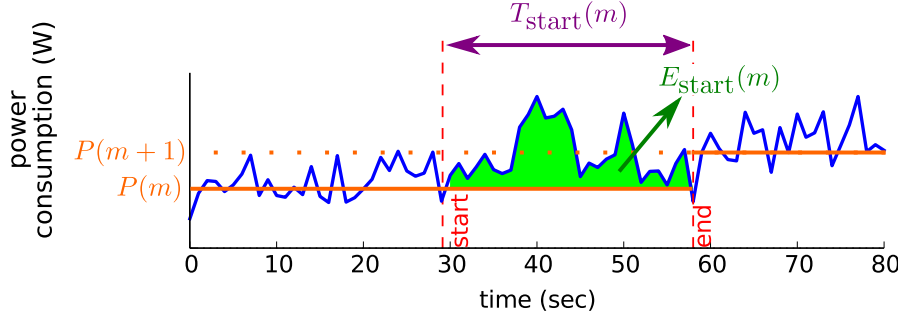


Figure 12: Power consumption and throughput according to GPU accelerator.

Parameters described in Table 5 are learned from a set of experiences by linear regression. In the following two sections, we present two realistic scenarios, and we validate the model in both cases. In Section 5, model parameters are learned from the experimental study previously presented. However, in a real environment, it is rarely feasible to perform the experimental scenarios of Section 3 to this end. So, in Section 6, we learn the model parameters from a single scenario on a running system.

5 Experimental results about model validation

In this section, we validate the model by a set of experiments. These experiments are also designed to show potential use cases of the model. As we have seen in the motivation example (Section 1), the proposed model aims at easing the working of energy-efficient VM management systems. The estimation of the energy consumption for the different options offered by the system gives information to conduct a “what-if” analysis.

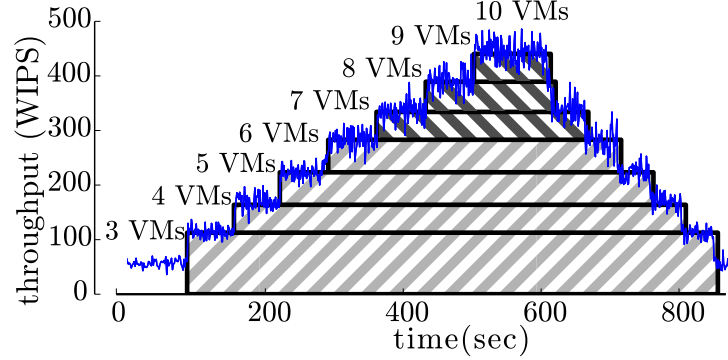
Experimental setup. We conduct experiments with the settings already described in Section 3 with the *ordering* profile workload.

5.1 First use-case: VM allocation

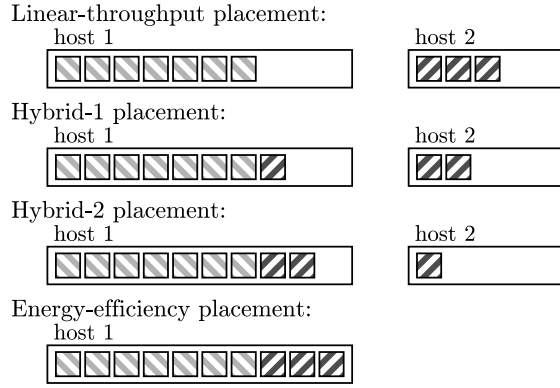
An efficient VM allocation depends on the energy consumed by the host and on the throughput produced by the VMs. We have seen in Section 3.1 that a small throughput degradation can achieve a high energy savings. In this case, we use the model to estimate the energy consumption of hosts in order to decide for the most suitable VM allocation.

We mimic a system having a workload peak which requires a variable number of VMs. Figure 13a shows the number of VMs required and the throughput produced in a real execution.

The 10 VMs required by the workload can be allocated in one host or can use two hosts. We exploit results from Section 3.1, to evaluate the four VMs placements described in Figure 13b. We have observed that throughput scales linearly until 7 VMs in the same host. Hence, to maintain linear throughput, the next 3 VMs are placed in other host (in the top of the figure). In another hand, placing 10 VMs in the same host has the largest energy savings with some throughput degradation (in the bottom of the figure). As intermediate placement between having linear throughput and having the largest energy savings, we propose two hybrid placements (in the middle of the figure).



(a) Throughput pattern for the first use-case



(b) Different VMs placements for the first use-case

Figure 13: Number of VMs required and throughput produced in a real execution.

We assume that the exact moments to start up and delete the VMs are known. This is not a major constraint in model validation, because the model's goal is to predict energy consumption of VM management operations and not real workload.

Figure 14 presents the results over 10 repetitions. For each possible placement, the figure shows the box plot of the relative error between the value estimated by the model and the real value. The model estimates the energy with a relative error lower than 4% (with average 1.50%). This experiment demonstrates the ability of the proposed model to accurately estimate the energy consumption of systems with peak loads.

5.2 Second use-case: starts and migrations together

VMs start-ups and migrations can happen together in the system and the model must be able to fit well also during concurrent operations.

For each host, every 300 seconds one VM management operation starts according to the scenario displayed on Figure 15. For example, for the host 1 allocating 1 initial VM: firstly, a VM starts at 300 sec (it has 2 VMs); then a VM is received from server 2 at 600 sec (it has 3 VMs); and finally, another VM migrated from server 3 arrives at 900 seconds (it has 4 VMs). The experiment finishes at 1200 sec.

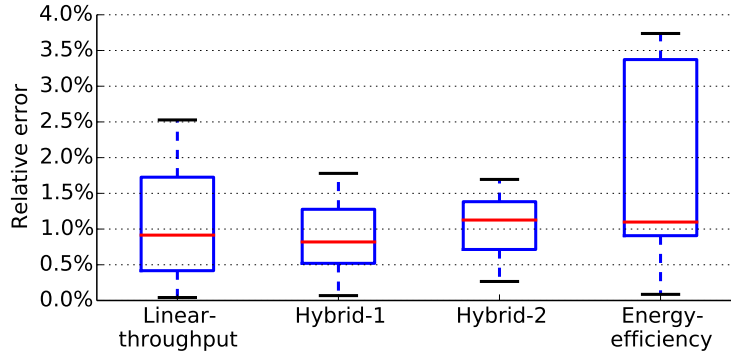


Figure 14: Relative error in the first use-case is lower than 4%.

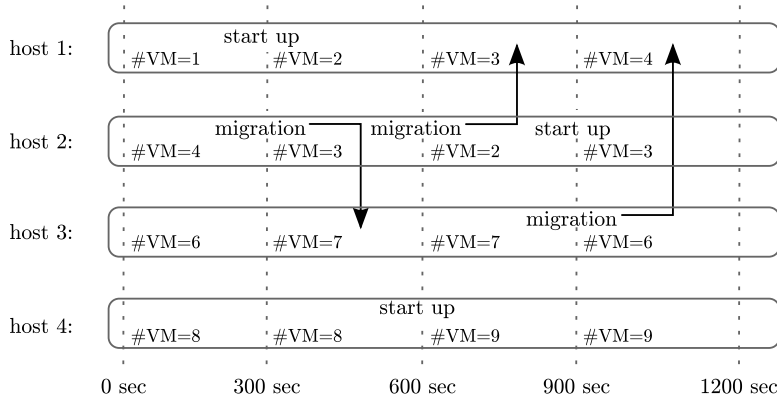


Figure 15: Start-up and migration events together in the second use-case.

Figure 16 presents the results over 10 repetitions. For each host, the figure shows the box plot of the relative error between the value estimated by the model and the real value. The model estimates the energy with a relative error lower than 7% (2.46% on average). This experiment shows that the model correctly grasps the energy consumption of systems where VM start-up and migrations happen together.

From the achieved results, we show that the proposed model performs well and is able to accurately estimate the energy consumption of VM management operations, even when different operations occur at the same time. In all cases, the obtained relative error between estimated and real values are below the 10% line, which is considered as a reasonable limit from literature (Section 2).

6 Learning model parameters in a real system

In a real running Cloud platform, it is not realistic to run the toy scenarios presented in Section 3 to set model parameters. This means the estimation of model parameters must be done by observing the system. In this section, we study how to learn VM consolidations from previous information. We present how to learn the model parameters from a realistic *training* scenario. We use another *test* scenario to evaluate the model accuracy.

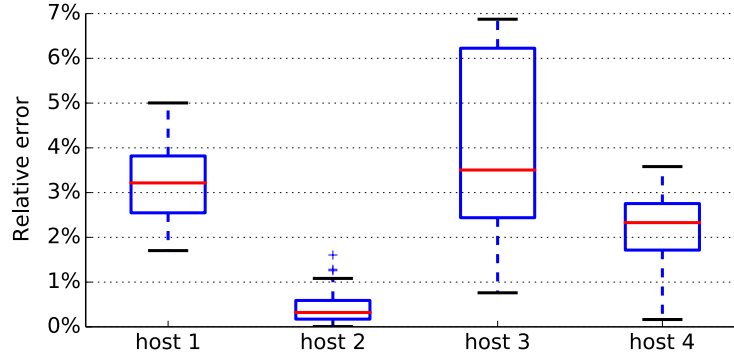


Figure 16: Relative error in the second use-case is lower than 7%.

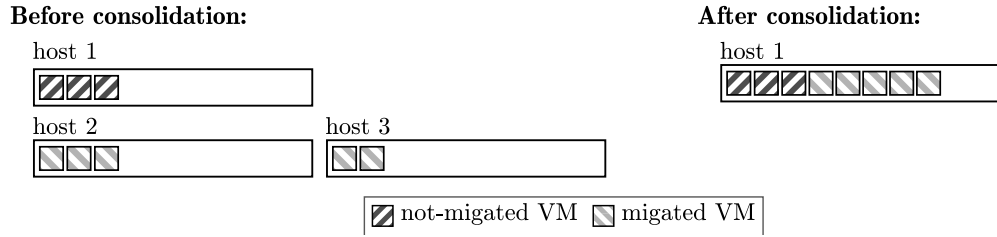


Figure 17: Training scenario for consolidation.

Training scenario. To learn the model, we start with three hosts allocating eight VMs as shown in Figure 17. Consolidation consists in migrating VMs running on hosts 2 and 3 to host 1. This means, after consolidation hosts 2 and 3 will be completely free. From this scenario, we infer the average duration and power consumption of migration in source and destination hosts.

Test scenario. In the training scenario, there are not much more choices about how to perform consolidations. However, in a system with more hosts there are different algorithms to perform consolidation – especially if hosts are heterogeneous. As we have seen in the motivation example (Section 1), each algorithm takes different migration choices implying different power consumption.

In the test scenario, we have four hosts with twelve VMs overall as shown in Figure 18 on the top. In order to have two provisioned hosts after consolidation, algorithms move VMs from hosts 3 and 4 to hosts 1 and 2. Figure 18 on the bottom shows the final configurations for three consolidation algorithms called *first-fit*, *balancing* and *hybrid*.

Results. The training set runs 5 times and the test set 15 times. Figure 19 shows the relative error in the energy estimation over the test set. For each consolidation algorithm, the figure shows the box plot of the relative error between the energy estimated by the model and the real consumption.

The average error is always lower than 10%. However, some error points are greater than 10%. Table 6 shows the percent of experiments having an error greater than 10%. This case occurs when the time actually spent in migration is larger than the estimated time. Although

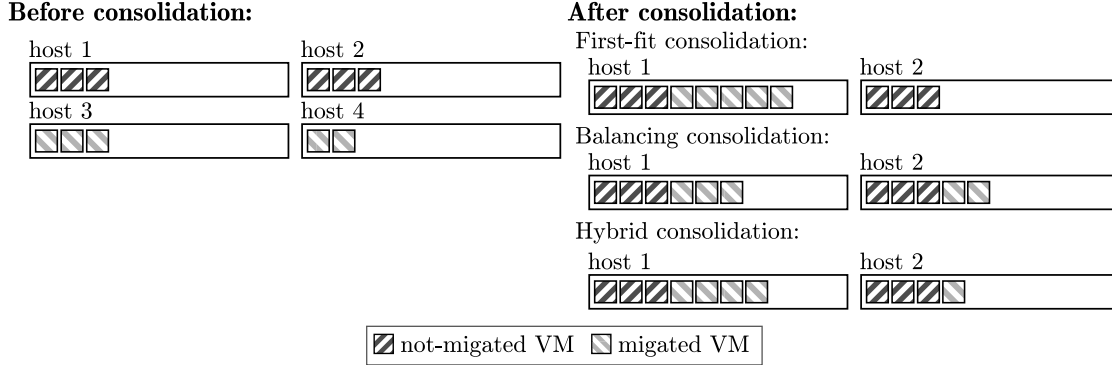


Figure 18: Test scenario for consolidation.

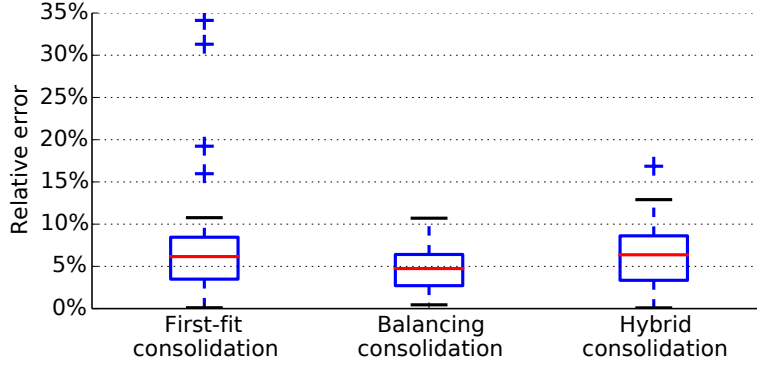


Figure 19: Average relative error is lower than 10% in test scenario.

the power consumption of the migration is correctly estimated, increasing the time spent in migration produces a bigger error.

7 Discussion

We have proposed an experiment-driven model to estimate the energy consumption associated to VM management operations. This model provides reliable and accurate energy consumption estimates required by energy-efficient VM management frameworks.

The proposed model is intended for online applications hosted by web servers where levels of resources utilization are fairly stable. For this reason, our model do not consider performance monitoring counters. In addition, the model does not cover the energy consumption on the network during migration, as done in [28] for instance. However, in order to target different workloads and network consumption, a complex model must be designed based on the principles settled in our model. On top of this solid basis, the next refinement of our model will consist in taking into account VM sizes.

In the experimental facts, energy consumption is confronted to throughput to better understand the energy-performance trade-off. Nevertheless, the presented model only address energy aspects. After the experimental investigations presented here, we believe an analogous model can be designed for performance, and it will be the target of a future work.

Table 6: Percent of runs having a relative error greater than 10% in test scenario.

First-fit consolidation	Balancing consolidation	Hybrid consolidation
17.24%	2.74%	14.71%

In addition to the “what-if” analysis enabled by the proposed model, the energy consumption dependence on the VM management operations shows a potential to increase energy savings in Cloud platforms. Energy savings could come from the opportunity to exchange resource-level and application-level information. While Infrastructure-as-a-Service (IaaS) energy-savings approaches actually provide energy savings, they can only base their decision on low-level metrics such as CPU usage, memory, I/O etc. However, these infrastructure-level metrics are insufficient to give enough insight in the behavior of applications which generate the load. Instead of treating applications as black boxes, we argue that significant energy savings could result from allowing the consolidation algorithms to access application-level knowledge present in the Platform-as-a-Service (PaaS) level of the Cloud stack. For example, only the PaaS layer can know if the workload is expected to decrease in the next few minutes producing the stop of some existing VMs. Making this information available in the consolidation system would allow to avoid costly and unnecessary actions such as migrating a VM while the PaaS plans to stop it soon. Such energy-related decisions could be taken by the IaaS using our model to perform the “what-if” analysis including PaaS information, and thus leading to cooperative energy saving strategies for Cloud platforms.

8 Conclusions

In this paper, we investigated the energy consumption associated to VM management operations such as VM placement, VM start up and VM migration. Firstly, we studied, through an extensive set of experiments, the performance and energy consumption, the impact of the different operations and the role of the number of running VMs on the considered hosts. Secondly, we propose a model for estimating the energy consumption with an average error lower than 10% for transactional web applications allowing overcommit situations.

As future work we will extend the evaluation to a wide range of applications, such as data intensive applications. Furthermore, we will introduce the throughput behavior in the model to estimate the throughput-energy trade-off providing a whole picture of the system.

References

- [1] Daniel Balouek, Alexandra Carpen Amarie, Ghislain Charrier, Frédéric Desprez, Emmanuel Jeannot, Emmanuel Jeanvoine, Adrien Lèbre, David Margery, Nicolas Niclausse, Lucas Nussbaum, Olivier Richard, Christian Pérez, Flavien Quesnel, Cyril Rohr, and Luc Sarzyniec. Adding virtualization capabilities to the Grid’5000 testbed. In IvanI. Ivanov, Marten Sinderen, Frank Leymann, and Tony Shan, editors, *Cloud Computing and Services Science*, volume 367 of *Communications in Computer and Information Science*, pages 3–20. Springer International Publishing, 2013. www.grid5000.fr.

- [2] Donato Barbagallo, Elisabetta Di Nitto, Daniel J. Dubois, and Raffaella Mirandola. A Bio-inspired Algorithm for Energy Optimization in a Self-organizing Data Center. In *First International Workshop on Self-Organizing Architectures*, SOAR '09, pages 127–151, 2009.
- [3] Salman A. Baset, Long Wang, and Chunqiang Tang. Towards an Understanding of Over-subscription in Cloud. In *USENIX Workshop on Hot Topics in Management of Internet, Cloud, and Enterprise Networks and Services (Hot-ICE)*. USENIX, 2012.
- [4] Anton Beloglazov, Jemal H. Abawajy, and Rajkumar Buyya. Energy-aware resource allocation heuristics for efficient management of data centers for Cloud computing. *Future Generation Computer Systems*, 28(5):755–768, 2012.
- [5] Anton Beloglazov and Rajkumar Buyya. Energy Efficient Allocation of Virtual Machines in Cloud Data Centers. In *10th IEEE/ACM International Conference on Cluster, Cloud and Grid Computing*, CCGrid '10, pages 577–578, 2010.
- [6] Ramon Bertran, Yolanda Becerra, David Carrera, Vicenç Beltran, Marc González, Xavier Martorell, Nacho Navarro, Jordi Torres, and Eduard Ayguadé. Energy accounting for shared virtualized environments under DVFS using PMC-based power models. *Future Generation Computer Systems*, 28(2):457–468, 2012.
- [7] Ata E. H. Bohra and Vipin Chaudhary. VMeter: Power modelling for virtualized clouds. In *24th IEEE International Symposium on Parallel and Distributed Processing - Workshop Proceedings*, IPDPS '10, pages 1–8, 2010.
- [8] Damien Borgetto, Henri Casanova, Georges Da Costa, and Jean-Marc Pierson. Energy-aware service allocation. *Future Generation Computer Systems*, 28(5):769–779, 2012.
- [9] David Breitgand, Zvi Dubitzky, Amir Epstein, Alex Glikson, and Inbar Shapira. SLA-aware Resource Over-commit in an IaaS Cloud. In *International Conference on Network and Service Management (CNSM)*, pages 73–81. International Federation for Information Processing, 2013.
- [10] Alexandra Carpen-Amarie, Anne-Cécile Orgerie, and Christine Morin. Experimental Study on the Energy Consumption in IaaS Cloud Environments. In *IEEE/ACM 6th International Conference on Utility and Cloud Computing*, UCC '13, pages 42–49, 2013.
- [11] Christopher Clark, Keir Fraser, Steven Hand, Jacob Gorm Hansen, Eric Jul, Christian Limpach, Ian Pratt, and Andrew Warfield. Live Migration of Virtual Machines. In *Proceedings of the 2nd Conference on Symposium on Networked Systems Design & Implementation*, NSDI'05, pages 273–286, 2005.
- [12] Maxime Colmant, Mascha Kurpicz, Pascal Felber, Loïc Huertas, Romain Rouvoy, and Anita Sobe. Process-level power estimation in VM-based systems. In *Proceedings of the Tenth European Conference on Computer Systems*, EuroSys '15, page 14, 2015.
- [13] SPECjbb2013 Benchmark. Standard Performance Evaluation Corporation. www.spec.org/jbb2013/.
- [14] Gaurav Dhiman, Kresimir Mihic, and Tajana Rosing. A system for online power prediction in virtualized environments using Gaussian mixture models. In *Proceedings of the 47th Design Automation Conference*, DAC '10, pages 807–812, 2010.

- [15] Anshul Gandhi, Varun Gupta, Mor Harchol-Balter, and Michael A. Kozuch. Optimality analysis of energy-performance trade-off for server farm management. *Performance Evaluation*, 67(11):1155–1171, 2010.
- [16] Qiang Huang, Fengqian Gao, Rui Wang, and Zhengwei Qi. Power Consumption of Virtual Machine Live Migration in Clouds. In *Third International Conference on Communications and Mobile Computing*, CMC '11, pages 122–125, 2011.
- [17] Amazon EC2 Instances. https://aws.amazon.com/ec2/instance-types/?nc1=h_ls.
- [18] Abhishek Jaiantilal, Yifei Jiang, and Shivakant Mishra. Modeling CPU Energy Consumption for Energy Efficient Scheduling. In *Proceedings of the 1st Workshop on Green Computing*, GCM '10, pages 10–15, 2010.
- [19] Aman Kansal, Feng Zhao, Jie Liu, Nupur Kothari, and Arka A. Bhattacharya. Virtual Machine Power Metering and Provisioning. In *Proceedings of the 1st ACM Symposium on Cloud Computing*, SoCC '10, pages 39–50, 2010.
- [20] Jonathan Koomey. Growth in data center electricity use 2005 to 2010. *Analytics Press*, August 2011.
- [21] Bhavani Krishnan, Hrishikesh Amur, Ada Gavrilovska, and Karsten Schwan. VM power metering: feasibility and challenges. *SIGMETRICS Performance Evaluation Review*, 38(3):56–60, 2010.
- [22] KVM: Kernel-based Virtual Machine. <http://www.linux-kvm.org>.
- [23] Hongjian Li, Guofeng Zhu, Chengyuan Cui, Hong Tang, Yusheng Dou, and Chen He. Energy-efficient migration and consolidation algorithm of virtual machines in data centers for cloud computing. *Computing*, pages 1–15, 2015.
- [24] Dan Liao, Ke Li, Gang Sun, V. Anand, Yu Gong, and Zhi Tan. Energy and performance management in large data centers: A queuing theory perspective. In *International Conference on Computing, Networking and Communications*, ICNC '15, pages 287–291, 2015.
- [25] Haikun Liu, Cheng-Zhong Xu, Hai Jin, Jiayu Gong, and Xiaofei Liao. Performance and energy modeling for live migration of virtual machines. In *Proceedings of the 20th ACM International Symposium on High Performance Distributed Computing*, HPDC '11, pages 171–182, 2011.
- [26] Martina Maggio, Henry Hoffmann, Alessandro V. Papadopoulos, Jacopo Panerati, Marco D. Santambrogio, Anant Agarwal, and Alberto Leva. Comparison of Decision-Making Strategies for Self-Optimization in Autonomic Computing Systems. *ACM Transactions on Autonomous and Adaptive Systems*, 7(4):36:1–36:32, 2012.
- [27] Vincenzo De Maio, Gabor Kecskemeti, and Radu Prodan. Workload-Aware Energy Model for Virtual Machine Migration. In *IEEE International Conference on Cluster Computing*, CLUSTER '15, 2015.
- [28] Vincenzo De Maio, Radu Prodan, Shajulin Benedict, and Gabor Kecskemeti. Modelling energy consumption of network transfers and virtual machine migration. *Future Generation Computer Systems*, 2015. In press, Accepted Manuscript.

- [29] Zoltán A. Mann. Rigorous results on the effectiveness of some heuristics for the consolidation of virtual machines in a cloud data center. *Future Generation Computer Systems*, 51:1 – 6, 2015.
- [30] Toni Mastelic, Ariel Oleksiak, Holger Claussen, Ivona Brandic, Jean-Marc Pierson, and Athanasios V. Vasilakos. Cloud Computing: Survey on Energy Efficiency. *ACM Computer Surveys*, 47(2):33:1–33:36, 2014.
- [31] Michele Mazzucco, Dmytro Dyachuk, and Ralph Deters. Maximizing cloud providers’ revenues via energy aware allocation policies. In *IEEE International Conference on Cloud Computing*, CLOUD ’10, pages 131–138, 2010.
- [32] Nikita Mishra, Huazhe Zhang, John D. Lafferty, and Henry Hoffmann. A Probabilistic Graphical Model-based Approach for Minimizing Energy Under Performance Constraints. In *Proceedings of the 20th International Conference on Architectural Support for Programming Languages and Operating Systems*, ASPLOS ’15, pages 267–281, 2015.
- [33] Christoph Mobius, Waltenegus Dargie, and Alexander Schill. Power Consumption Estimation Models for Processors, Virtual Machines, and Servers. *IEEE Transactions on Parallel and Distributed Systems*, 25(6):1600–1614, 2014.
- [34] Nvidia Corporation. www.nvidia.com/object/what-is-gpu-computing.html#sthash.TDnNYEDE.dpuf.
- [35] OpenStack Project. OpenStack: The open source cloud operating system. openstack.org.
- [36] Anne-Cecile Orgerie, Marcos Dias de Assuncao, and Laurent Lefèvre. A survey on techniques for improving the energy efficiency of large-scale distributed systems. *ACM Computing Surveys*, 46(4), 2014.
- [37] Anne-Cécile Orgerie, Laurent Lefèvre, and Jean-Patrick Gelas. Demystifying energy consumption in Grids and Clouds. In *International Green Computing Conference 2010*, IGCC ’10, pages 335–342, 2010.
- [38] Paula Petrica, Adam M. Izraelevitz, David H. Albonesi, and Christine A. Shoemaker. Flicker: A Dynamically Adaptive Architecture for Power Limited Multicore Systems. *ACM SIGARCH Computer Architecture News*, 41(3):13–23, 2013.
- [39] Srinath Sridharan, Gagan Gupta, and Gurindar S. Sohi. Holistic Run-time Parallelism Management for Time and Energy Efficiency. In *Proceedings of the 27th International ACM Conference on International Conference on Supercomputing*, ICS ’13, pages 337–348, 2013.
- [40] Anja Strunk. Costs of Virtual Machine Live Migration: A Survey. In *Eighth IEEE World Congress on Services*, SERVICES ’12, pages 323–329, 2012.
- [41] Anja Strunk. A lightweight model for estimating energy cost of live migration of virtual machines. In *2013 IEEE Sixth International Conference on Cloud Computing*, CLOUD ’13, pages 510–517, 2013.
- [42] Anja Strunk and Waltenegus Dargie. Does Live Migration of Virtual Machines Cost Energy? In *IEEE 27th International Conference on Advanced Information Networking and Applications*, AINA ’13, pages 514–521, 2013.

- [43] Petter Svärd, Benoit Hudzia, Steve Walsh, Johan Tordsson, and Erik Elmroth. Principles and Performance Characteristics of Algorithms for Live VM Migration. *SIGOPS Operating Systems Review*, 49(1):142–155, 2015.
- [44] TPC Benchmark W (Web Commerce) Specification. version 1.0.1, 2000. www.tpc.org/tpcw.
- [45] Akshat Verma, G. Kumar, R. Koller, and A. Sen. CosMig: Modeling the Impact of Re-configuration in a Cloud. In *International Symposium on Modeling, Analysis Simulation of Computer and Telecommunication Systems (MASCOTS)*, pages 3–11, July 2011.
- [46] Xen. <http://www.xenproject.org>.
- [47] Kejiang Ye, Xiaohong Jiang, Dawei Huang, Jianhai Chen, and Bei Wang. Live Migration of Multiple Virtual Machines with Resource Reservation in Cloud Computing Environments. In *Cloud Computing (CLOUD), 2011 IEEE International Conference on*, pages 267–274, July 2011.



**RESEARCH CENTRE
RENNES – BRETAGNE ATLANTIQUE**

Campus universitaire de Beaulieu
35042 Rennes Cedex

Publisher
Inria
Domaine de Volveau - Rocquencourt
BP 105 - 78153 Le Chesnay Cedex
inria.fr

ISSN 0249-6399